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Adaptive Matching for Compact MIMO Systems

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***Abstract*—Compact MIMO systems using closely spaced antennas are faced with the well-known problem of antenna mutual coupling (MC) that can degrade the performance. Previous studies have shown that a proper choice of antenna load impedances can maximise the MIMO capacity or received power in the presence of MC. However, to calculate this optimum load, prior knowledge of the propagation channel matrix and the MC model, which is difficult to measure practically, are required. In this paper, we present an adaptive matching approach for the receiver that directly deals with the received signals rather than the channel and MC models, to find optimum load impedances which maximise the MIMO capacity or received power.**

***Index Terms*—MIMO; performance; capacity; received power; mutual coupling; impedance matching; adaptive matching**

I. Introduction

Multiple-Input Multiple-Output (MIMO) technology, by using multiple antennas at both transmit and receive sides of the wireless link, offers a better link quality and higher data-rates [1]. However, applying MIMO at small wireless devices suffers from antenna mutual coupling (MC) which degrades the MIMO channel capacity [2]–[6]. Among previous studies, choosing the load impedances has been presented as a solution to control the radiation pattern of coupled antennas and thus the MIMO capacity and/or received power. There are two methods which either use a complex coupled matching network called a *multiport-conjugate match* [2], [3] or apply a simple uncoupled network called a *single/individual-port match* [4], [6]–[8]. It has been claimed that multiport matching network offers a significant capacity improvement but only for small bandwidths, while the individual-port matching network is simpler to implement and offers a broader bandwidth by finding an optimum load impedance for a given propagation environment [6], [8]. However, both methods require a prior knowledge of the propagation channel and an accurate MC model which is difficult to measure in practice. They use open-circuit voltages and scattering-parameters, respectively, to describe the MC among the transmit and receive antennas. In [9], [10] it has been claimed that those methods are not capable of modeling MC at the receiving array properly.

In this paper, we concentrate on the receive side of the MIMO system and propose an adaptive matching approach that directly deals with the received signals to find an uncoupled optimum load match which maximises the capacity or received power. Having used the received signals, the realistic effects of the propagation channel and the MC will be incorporated in the calculation process. We numerically show how this method performs for different propagation environments.

The remainder of this paper is organised as follows. Section II gives a review of the Z-parameter representation of the MIMO system model. In section III, we derive capacity and received power expressions based on the received signals over a time interval. This is followed by a description of the adaptive matching method in section IV, which is treated as a random search for the uncoupled optimum load by using a smart step size. In section V, numerical results to optimise the mean capacity are performed to validate the proposed algorithm. We conclude the paper in Section VI.

II. MIMO model

We consider a MIMO system of M_T transmit and M_R receive antennas, communicating through a frequency-flat fading channel. The relationship between the transmit signal vector $\mathbf{x}(t) \in \mathbb{C}^{M_T}$ and the receive signal vector $\mathbf{y}(t) \in \mathbb{C}^{M_R}$ at time t is given by

$$\mathbf{y}(t) = \mathbf{H}\mathbf{x}(t) + \mathbf{n}(t) \tag{1}$$

where $\mathbf{H} \in \mathbb{C}^{M_R \times M_T}$ is the channel gain matrix including MC effect, and $\mathbf{n}(t) \in \mathbb{C}^{M_R}$ represents a vector of additive white Gaussian noise at the receiver, which is assumed to be a complex Gaussian noise with zero-mean and covariance matrix $\sigma_n^2 \mathbf{I}_{M_R}$ where $\mathbf{I}_{M_R}$ is a $M_R \times M_R$ identity matrix. For the sake of simplicity, given a transmit power constraint P_T, we consider an equivalent model for (1) with a unit-variance noise and transmit power P_T/σ_n^2. Having $\mathbf{R_x}$ as the covariance matrix of the input vector $\mathbf{x}$, the output covariance matrix $\mathbf{R_y}$ associated with the received signal vector $\mathbf{y}$ can be written as:

$$\begin{aligned}\mathbf{R_y} &= \mathcal{E}\{\mathbf{y}\mathbf{y}^H\} \\ &= \mathbf{H}\mathcal{E}\{\mathbf{x}\mathbf{x}^H\}\mathbf{H}^H + \mathcal{E}\{\mathbf{n}\mathbf{n}^H\} \\ &= \mathbf{H}\mathbf{R_x}\mathbf{H}^H + \mathbf{I}_{M_R}\end{aligned} \tag{2}$$

where $(\cdot)^H$ is conjugate-transpose operator, and $\mathbf{x}$ and $\mathbf{n}$ are assumed to be uncorrelated. In other words, $\mathcal{E}\{\mathbf{x}\mathbf{n}^H\} = \mathcal{E}\{\mathbf{n}\mathbf{x}^H\} = \mathbf{0}$.

III. MIMO Capacity and Received Power

The well-known MIMO channel capacity expression is given by

$$C = \log_2 \det(\mathbf{I}_{M_R} + \mathbf{H}\mathbf{R_x}\mathbf{H}^H) \tag{3}$$

We note that accurately measuring the channel matrix for closely coupled antennas, taking MC modeling into account, is difficult practically. So it is easier if we can work with the received signal $\mathbf{y}$. However, this is limited by the fact that in order to optimise the impedance we need to directly try out different impedance choices and see the effect on the capacity/received power.

Looking at (2) and (3), it is clear that we could use (an estimation of) the covariance matrix of the received signals to calculate the capacity, rather than estimating a channel model including MC effect. One way of implementing this idea is substituting a time averaging estimation of $\mathbf{R}_\mathbf{y}$ into the argument of $\log_2 \det$ function at (3) as follows

$$C = \log_2 \det \left(\frac{1}{L} \sum_{i=t_0}^{t_0+L-1} \mathbf{y}[i]\mathbf{y}^H[i] \right) \tag{4}$$

where t_0 is the starting sample time, L is the data-block length, and i is the time index for discrete-time samples. We further assume that the block length L is long enough for equation (2) to hold, and that $\mathbf{H}$ does not change over each data block. Now, we have an expression for the capacity that includes propagation channel properties and MC effects by having a block of received data with no further parameters required.

Assuming $\mathbf{y}(t)$ is the received voltage vector across the load terminals of receive antennas, the received power for ith antenna can be written as

$$P_{r,i} = \mathcal{E}\{\frac{y_i(t)y_i^*(t)}{R_{L,i}}\}/P_0, \qquad i = 1, \cdots, M_R \tag{5}$$

where $(\cdot)^*$ denotes conjugate operator, $R_{L,i}$ represents the real part of the load terminal $Z_{L,i}$ for antenna i, and P_0 is the power received by a conjugate matched isolated antenna which is used to normalise the MIMO received power. Here we assume all received antennas are terminated with identical loads. So, the total mean received power can be expressed as $P_r = \mathcal{E}\{\mathbf{y}(t)\mathbf{y}^H(t)/R_L\}/P_0$. Similar to the estimation procedure for the capacity, we can estimate the total received power from the following expression

$$P_r = \frac{1}{P_0} \left(\frac{1}{LR_L} \sum_{i=t_0}^{t_0+L-1} \mathbf{y}[i]\mathbf{y}^H[i] \right) \tag{6}$$

IV. Adaptive Match Algorithm

In this section, we describe the proposed algorithm to find the optimum impedance match for an arbitrary propagation environment in the presence of the MC effects. As we mentioned in the previous section, we have to try out different load impedances and calculate the capacity and received power from (4) and (6) for each load. This allows us to find the optimum load which maximises the capacity or received power. One way is to try a possible range of load impedances and find the optimum load which corresponds to the maximum peak of the capacity or received power. This method has a high computational load and needs a large memory to keep all data. Furthermore, we have to repeat this process for different channel propagation conditions. Obviously, it is not practical specially for small portable wireless devices.

Instead, we propose an adaptive matching algorithm that uses fewer load impedances and has much lower computational burden. The algorithm starts a random search [1] for the optimum load impedance from an initial impedance Z_L^0 (for instance 50Ω), and for each step m selects a terminal impedance as follows

$$\begin{aligned} Z_L^m &= Z_L^{m-1} + (\Delta_R + j\Delta_X) \\ &= (R_L^{m-1} + \Delta_R) + j(X_L^{m-1} + \Delta_X) \end{aligned} \tag{7}$$

where R_L^{m-1} and X_L^{m-1} are the real and imaginary parts of the load impedance Z_L^{m-1} at step $(m-1)$, and Δ_R, Δ_X are randomly selected step sizes from the set $\{-\Delta, 0, \Delta\}$ for a given Δ, but are not equal to zero simultaneously. At each step, the mean capacity/received power, which is calculated by averaging the capacity/received power from equations (4) or (6) over K data-blocks, is compared with the previous value. The impedance which corresponds to the greater mean capacity/received power is hold as the optimum Z_L at each step.

In this work, we have considered a variable step size Δ to have a faster convergence. We start from a large value such as $\Delta = 16\Omega$ and then decrease it after having a specific number of unchanged choices for optimum Z_L, by dividing the present Δ over 2 for $\Delta \geq 2\Omega$.

V. Numerical Results

To investigate the proposed adaptive matching algorithm, some simulations for a 3×3 MIMO system of half-wavelength dipoles with identical loads at antenna spacing $d = 0.05\lambda$ is carried out. We optimize the mean capacity under different propagation environments: 2D uniform, and 2D Laplacian defined by the mean ϕ_0 and the standard deviation σ of the distribution, for two signal-to-noise-ratios (SNR) 5 and 20dB at the receiver. We assume the transmit antennas to be separated far enough (negligible MC effect at the transmit side) and to be self-impedance conjugate matched. The mean capacity is calculated from (4) for both non-adaptive and adaptive matching methods. The received signal vector $\mathbf{y}$ is calculated from (1) by generating a complex Gaussian transmit signal $\mathbf{x}$ with zero-mean and $\sigma_x^2 = SNR = \{5, 20 \text{ dB}\}$ variance, and the channel matrix given by [8]

$$\mathbf{H} = 2\sqrt{R_{11}R_L}(Z_L\mathbf{I} + \mathbf{Z}_R)^{-1}\mathbf{\Psi}_R^{1/2}\mathbf{H}_w\mathbf{\Psi}_T^{1/2} \tag{8}$$

where R_{11} and R_L denote the real parts of the self-impedance Z_{11} and terminal load Z_L of the antennas, and $\mathbf{Z}_R$ represents the antennas mutual impedance matrix [13]. The matrix $\mathbf{H}_w$ entries are complex Gaussian random variables of zero-mean and average power of unity, $\mathbf{\Psi}_T$ and $\mathbf{\Psi}_R$ are the spatial correlation matrices at the transmit and receive ends, respectively. Furthermore, we assume $\mathbf{\Psi}_T = \mathbf{I}$, data block length $L = 2000$, and $K = 2000$ data blocks.

Fig. 1 shows contour plots of the mean capacity versus real and imaginary parts of $Z_L = R_L + jX_L$ where $R_L \in (0, 100]\Omega$

[1]This idea is motivated by random phase selection [11] and random walk [12] algorithms.

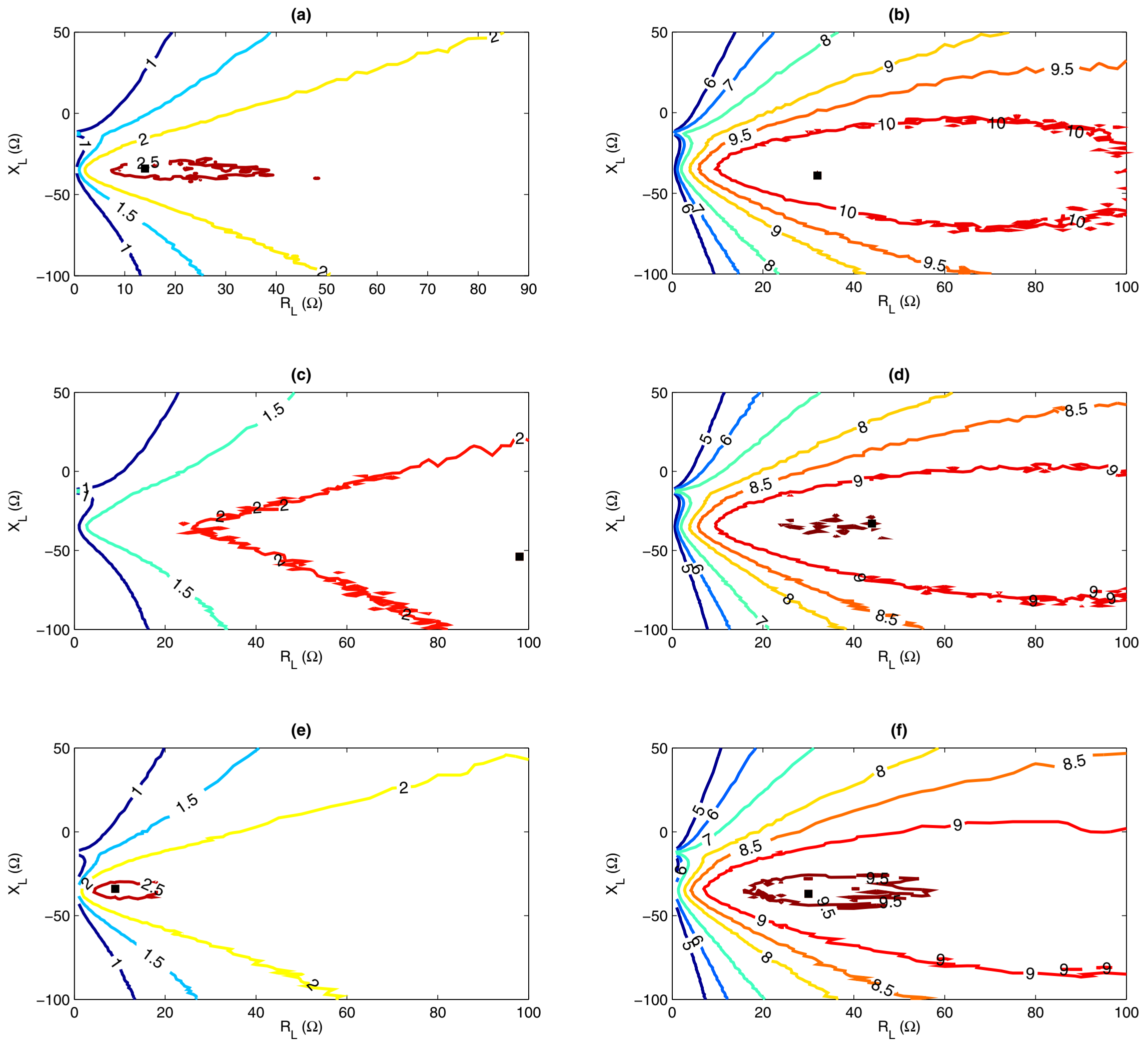

Fig. 1. Mean capacity versus real and imaginary parts of the antenna load impedance Z_L for uniform ((a) and (b)) and Laplacian distributions with $(\phi_0, \sigma) = (0°, 40°)$ at (c)-(d), and $(90°, 67°)$ at (e)-(f). Signal to noise ratio 5 dB for (a),(c),(e) and 20 dB for (b),(d) and (f) is considered. The optimum loads which maximise the mean capacity are marked by black squares for all cases.

and $X_L \in [-100, 50]\Omega$, for different propagation scenarios: uniform (a)-(b), and Laplacian with $(\phi_0, \sigma) = (0°, 40°)$ for (c)-(d), and $(90°, 67°)$ for (e)-(f). We note that the magnitudes of the correlation coefficient for these two set of Laplacian paramteres are equal. The received $SNR = 5$dB for the left column (subfigures (a),(c),(e)) and 20 dB for (b),(d) and (f) is considered. It can be seen that the mean capacity at any case can be maximized by selecting a proper load Z_L (black square marked points). Comparing the maximum values of the mean capacity and the the corresponding loads in Table I reveals that the optimum load depends on different factors of the propagation environment. Therefore, existence of an adaptive matching approach would be necessary in practice.

TABLE I
OPTIMIZED MEAN CAPACITY AND THE CORRESPONDING LOAD IMPEDANCES $Z_L(\Omega)$ FOR THE UNIFORM AND LAPLACIAN (ϕ_0,σ) SCATTERING DISTRIBUTIONS.

Capacity (bits/s/Hz)	Uniform	$(0^o, 40^o)$	$(90^o, 67^o)$
$SNR = 5dB$	2.5816	2.179	2.6114
$SNR = 20dB$	10.5135	9.5632	9.6118
Optimum $Z_L(\Omega)$	Uniform	$(0^o, 40^o)$	$(90^o, 67^o)$
$SNR = 5dB$	$14 - j34$	$98 - j54$	$9 - j34$
$SNR = 20dB$	$32 - j39$	$44 - j33$	$30 - j37$

The results of 100 Monte Carlo runs of the adaptive matching algorithm with initial load $Z_0 = 50\Omega$ and 50 steps per execution, are shown with asterisk marked points in Fig.

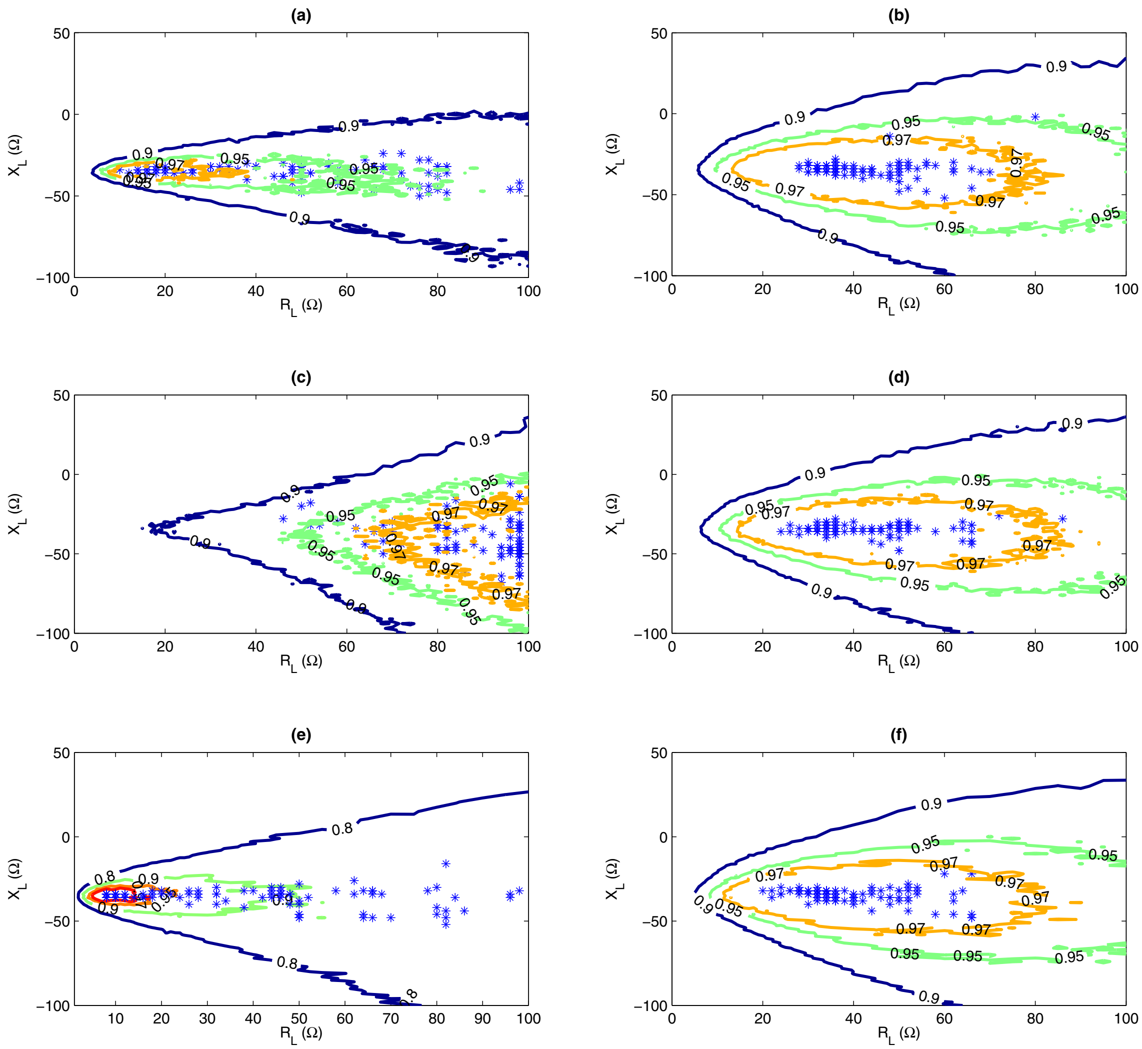

Fig. 2. Adaptive matching results for 100 runs (asterisk marked points) with initial load $Z_0 = 50\Omega$ and normalized mean capacity contour for uniform ((a) and (b)) and Laplacian distributions with $(\phi_0, \sigma) = (0°, 40°)$ at (c)-(d), and $(90°, 67°)$ at (e)-(f). $SNR = 5$ dB for (a),(c),(e) and 20 dB for (b),(d) and (f) is considered.

2. Additionally, the mean capacity contours normalized to their corresponding maximum values are plotted to evaluate the adaptive algorithm results. We observe that the adaptive algorithm has found an optimum load which gives a mean capacity higher than 97% of the maximum C_{mean} at Table I for $SNR = 20$dB. For the lower SNR case, algorithm still goes to the area of 97% of the maximum C_{mean} for some propagation senario (c), but not for the others. This problem could be solved by trying different intial load impedances or longer block lengths L.

As it is shown in the simulation results, the proposed adaptive matching algorithm can be used to improve the compact MIMO performance by choosing a proper antenna load impedance based on the received signals. This algorithm does not require any knowledge of the channel or MC model which are practical issues for previous studies. So, it could be a practical solution to deal with MC effects in compact MIMO systems.

VI. Conclusion

In this paper, we investigated the effect of antenna load impedance on the MIMO performances based on the receiving signals. Then we proposed an adaptive matching algorithm that can find a proper load impedance to maximise the MIMO capacity and/or received power in the presence of MC. This optimisation is performed directly on the received signals and requires no prior knowledge of the channel matrix and MC modeling which are the practical issues for the present studies. Simulation results are shown to illustrate the ability of the proposed algorithm to improve compact MIMO performance in the presence of MC.

REFERENCES

[1] A. Goldsmith, *Wireless Communications*, New York,USA 2005.

[2] J. W. Wallace, and M. A. Jensen, "Mutual coupling in MIMO wireless systems: a rigorous network theory analysis," *IEEE Transactions on Wireless Communications*, vol. 3, pp. 1317-1325, Jul. 2004.

[3] J. W. Wallace, and M. A. Jensen, "Termination-dependent diversity performance of coupled antennas: network theory analysis," *IEEE Transactions on Antennas and Propagation*, vol. 52, pp. 98-105, Jan. 2004.

[4] J. B. Andersen, and B. K. Lau, "On Closely Coupled Dipoles in a Random Field," *IEEE Antennas and Wireless Propagation Letters,* vol. 5, no. 1, pp. 73-75

[5] B. K. Lau, J. B. Andersen, A. F. Molisch, and G. Kristensson, "Antenna Matching for Capacity Maximization in Compact MIMO Systems ," *ISWCS '06. 3rd International Symposium on Wireless Communication Systems*, pp. 253-257, Sep. 2006.

[6] B. K. Lau and J. B. Andersen, "On Closely Coupled Dipoles with Load Matching in a Random Field," *IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1-5, Sep. 2006.

[7] M. A. Jensen, and B. Booth,"Optimal uncoupled impedance matching for coupled MIMO arrays," *EuCAP 2006*, pp. 1-4, Nov. 2006.

[8] Y. Fei, Y. Fan, J. S. Thompson, and B. K. Lau,"Optimal single-port matching impedance for capacity maximization in compact MIMO arrays," *IEEE Transactions on Antennas and Propagations*, vol. 56, pp. 3566-3575, Nov. 2008.

[9] H. T. Hui,"Decoupling methods for the mutual coupling effect in antenna arrays: a review," *Recent Patents on Engineering*, vol. 1, pp. 187-193, 2007.

[10] H. T. Hui,"Compensating for the mutual coupling effect in direction finding based on a new calculation method for mutual impedance," *IEEE Antennas and Wireless Propagation Letters*, vol. 2, pp. 26-29, 2003.

[11] R. Mudumbai, D.R. Brown, U. Madhow, and H.V. Poor, "Distributed transmit beamforming: challenges and recent progress," *IEEE Communications Magazine*, vol. 47, pp.102-110, Feb. 2009.

[12] D. Aldous and J. Fill, *Reversible Markov Chains and Random Walks on Graphs*, Available: http://stat-www.berkeley.edu/users/aldous/RWG/book.html.

[13] C. A. Balanis, *Antenna Theory: Analysis and Design*, John Wiley, 1997.